The volcanic history of Furnas volcano, S. Miguel, Azores

J.E. Guest [1], J.M. Pacheco [2], P.D. Cole[3], A.M. Duncan[4,5], N. Wallenstein [2], G. Queiroz [2], J.L. Gaspar [2] , T. Ferreira [2]

[1] Department of Earth Sciences, University College London, London WC1E 6BT, UK

[2] Centro de Vulcanologia e Avaliação de Riscos Geológicos da Universidade dos Açores, CVARG, Rua da Mãe de Deus, 9500-321 Ponta Delgada, Açores, Portugal

[3] School of Geography, Earth & Environmental Sciences, University of Plymouth, Plymouth PL4 8AA, UK

[4] Institute of Biological, Environmental Science & Technology, University of Bedfordshire, Luton LU1 3JU, UK

[5] Department of Geography and Planning, University of Liverpool, Liverpool L69 3BX, UK

*Corresponding author: Angus Duncan (e-mail: angus.duncan@beds.ac.uk)

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Abstract: Furnas is the easternmost of the trachytic active central volcanoes of S. Miguel. Unlike the other central volcanoes, Sete Cidades and Fogo, Furnas does not have a substantial edifice built up above sea level. Though not as dominant as the other two volcanoes, Furnas does, however, have an edifice rising from the basal basaltic lavas exposed on the north coast to around 600 m asl on the northern rim of the main caldera. In common with Sete Cidades and Fogo, Furnas had major trachytic explosive eruptions in its volcanic history which emplaced welded ignimbrites. In the last 5 ka Furnas has had 10 moderately explosive trachytic eruptions of Sub-Plinian character, two of these have taken place since the island was settled in the mid-15th century. A future eruption of Sub-Plinian magnitude is a major hazard posed by Furnas volcano. Even when not in eruption Furnas is a hazardous environment. Its fumarolic fields discharge high levels of CO_2 and concentrations in some area of Furnas village present a risk to health; the steep slopes and poorly consolidated volcanic materials are prone to landslides in particular when triggered by earthquakes or as was the case in 1997, when landslides caused severe damage and casualties in Ribeira Quente following heavy rain.

Of the three trachytic central volcanoes on S. Miguel, Furnas is topographically the least impressive. The other two, Sete Cidades and Fogo, have well defined cone-like forms with summits truncated by calderas. Furnas, on the other hand, does have a morphologically impressive caldera-complex especially when viewed from its rim (Fig. 1). It is considered to be an active volcano having had at least ten eruptions during the past 5,000 years, including two historic ones in 1439/43 AD and 1630 AD. It also has an active geothermal system.

Furnas abuts against the west flank of the older Povoação volcano and the rims of the calderas of each volcano are in contact. To the west its deposits inter-finger with those of the basaltic lava fan of the Congro Fissural Volcanic system which lies between Fogo volcano and Furnas.

Furnas is deeply dissected by stream erosion in this area of heavy rainfall. Steep sided valleys provide good outcrops where access is available and the lush vegetation cover is cleared. Landslides are common, especially during heavy storms, and provide additional outcrops. Some of the best outcrops occur in the sea cliffs, although some areas are only accessible by boat. On the southern coast, which is almost entirely cut into poorly indurated pyroclastic rocks, narrow tracks have been excavated to link agricultural terraces, and to provide communication by foot between coastal fishing villages. Apart from the sea cliffs, continuity between outcrops is poor and untangling the stratigraphy of this volcano is difficult.

Much of this paper on the history of Furnas volcano is summarized from the stratigraphical work of Guest *et al.* (1999), but new work on the early history is included together with a fuller description of Furnas C, the major eruption of the last 5,000 years.

Previous work

Furnas was designated a European Laboratory Volcano in 1993, and became the subject of a European Union Framework funded project between 1993 and 1996. The results of this project were presented in a thematic volume of *Journal of Volcanology and Geothermal Research* (eds, Duncan *et al.* 1999) which covered geological, petrological, geochemical, geophysical, geothermal and hazard aspects of the volcano. In the 1999 volume, the morphology, stratigraphy and structure of Furnas was documented in detail by Guest *et al.* (1999). Other papers on the geology of Furnas included those by: Cole *et al.* (1999) on styles of eruption; Duncan *et al.* (1999) on the Povoação ignimbrite the largest eruption to have occurred on Furnas and Jones *et al.* (1999) on eruption frequency. The most recent eruption of Furnas in 1630 and its products is described in Cole *et al.* (1995), and Queroz *et al.* (1995) report on other historically documented volcanic activity.

Before the EU Laboratory Volcano study, discussions of Furnas were included in papers that covered more than one of the volcanoes of S. Miguel. Two seminal papers by George Walker and his group provided a major contribution. The first, on two Plinian-type eruptions of Fogo (Walker & Croasdale 1971), the deposits of Fogo A being an important stratigraphic marker on Furnas as well as for the Picos Fissural Volcanic System. The second, a broader study of the volcanism of S. Miguel as a whole, in which a stratigraphy for tephra deposits on the island during the past 5000 years was established; and the hazard from volcanic events discussed and quantified (Booth *et al.* 1978). Richard Moore of the US Geological Survey geologically mapped the whole of S. Miguel (Moore 1991a) and from this interpreted the geological history of the three trachytic centres, including Furnas. He also, discussed potential hazards from future eruptions (Moore 1991b).

General morphology of Furnas Volcano

The Furnas caldera is roughly elliptical in plan view and is a nested caldera complex (Guest *et al.* 1999). The Main (outer) caldera is about 8 x 5 km in diameter, with its long axis oriented NE-SW. The outer walls of the Main caldera form steep cliffs to the N and also to the NE where it cuts into the Povoação caldera wall. To the W and S the caldera boundary is less well defined being partly buried by products of later eruptions (Fig. 2).

The Inner caldera (6 x 3.5 km) also cuts the Povoação caldera as well as the Furnas Main caldera rim to the E. To the N and W it bites into deposits of the Main caldera fill, so providing exposures of deposits formed by activity between the two major caldera collapses on the volcano. To the south, the caldera wall is obscured by post-caldera

deposits. At least two other small collapses (less than 2 km across) have occurred within the Inner caldera.

The southern rim of the volcano is cut by marine erosion to form high, steep cliffs that provide the most continuous stratigraphic exposure on Furnas. Proximity of the cliff to the main caldera rim implies that the exposed deposits are proximal in nature, and the characteristics of many of them confirm this.

Trachytic cones occur within the Main caldera and on its margin. Young pumice cones (< 5,000 years) are distributed on the floor of the Inner caldera (Fig. 1), whereas young basaltic cones (< 5,000 years) are restricted to outside the Main caldera mainly to the north.

Basal lavas

The two other trachytic central volcanoes on S. Miguel (i.e. Fogo and Sete Cidades) each sit on top of a pile of lavas rising from the ocean floor (Queiroz *et al.* 2015 and Wallenstein *et al.* 2015, both this volume). Guest *et al.* (1999) described Furnas as essentially a trachytic centre of pyroclastic and dome forming rocks showing a limited intercalation of lavas of more mafic composition. These authors accepted the long held opinion (Moore 1990) that the lava pile at the NE end of the island represented an older, deeply dissected construct. Supporting this view is the lack of a thick sequence of lavas in the coastal cliffs to the south of the Furnas caldera. Guest *et al.* (1999) did, however, consider that Povoação was a distinct centre associated with the caldera of that name, and referred generally to the Povoação/Nordeste lava complex against which the Furnas trachytic centre abuts. Further work (Duncan *et al.* 2015, this volume) has identified an old highly dissected Nordeste Volcanic System which is older than Povoação volcano. There remains the lava pile north of the Furnas centre previously mapped as part of the Nordeste lava pile (e.g. Moore 1991a). We now consider that the lava pile directly to the north of Furnas Main caldera is the lava basement of the Furnas construct.

The main criterion for distinguishing between the Nordeste lava pile and the Povoação centre is the degree of dissection. Povoação, despite being cut by deep canyons, retains its caldera form and flanks, whereas Nordeste does not (Duncan *et al*. 2015, this volume). Instead it is deeply dissected by canyons, cut by high fault scarps and, in places, rocks are deeply weathered. By comparison, the lava slope north of Furnas caldera, is less dissected by fluvial erosion than the northern flanks of Povoação. This would indicate that these basaltic lavas are part of the emergent lava base of Furnas volcano. In addition the valleys here are radial with respect to the Furnas centre (which reaches an altitude of around 600 m asl on the northern rim of the Main caldera) and not to Povoação or Nordeste (Fig. 3). If this interpretation is correct, then Furnas - like Fogo and Sete Cidades volcanic systems - has a lava-built basement. It also begs the question as why this is not present on the southern flank. For a possible answer we look

at the adjacent Povoação volcano where the southern flank has also been extensively eroded along the coast, in this case as a result of the combination, not only of marine erosion, but also faulting (Duncan *et al.* 2015, this volume).

Stratigraphy

The stratigraphy of Furnas is summarised in Table 1 which is adapted from Figure 7 in Guest *et al.* (1999, p14) and in this brief overview we only highlight its principal features and present new material. For fuller information reference should be made to Guest *et al.* (1999). Available radiometric dates are also shown in Table 1. Mention should be made of issues regarding radiocarbon dating both on this volcano and other places where soil degassing of magmatic CO_2 is present (see Guest *et al.* 1999, p13-16).

Pre-older Main caldera history

As discussed above, the presence of an initial basaltic pile is now proposed for Furnas volcano. The basaltic lavas that underlie Furnas volcanic products to the east of Ribeira Quente are attributed to Povoação and not Nordeste volcano as originally indicated by Guest *et al.* (1999). Underlying lavas to the west of Ribeira Quente may be a continuation of Povoação volcano or possibly the basal lavas of Furnas volcano. The lava pile exposed on the north coast to the east of Maia is considered to be the basal lavas of Furnas volcano.

The deposits that lie between the Basal Lavas and formation of the Main caldera are assigned by Guest *et al.* (1999) to the Lower Furnas Group. The Lower Furnas Group is composed of ignimbrites, thick pumice lapilli beds, ash fall beds, debris flow deposits, a block and ash flow deposit and some trachytic lavas. This sequence reflects predominantly major explosive activity involving silicic magmas. The top of the Lower Furnas Group is marked by a distinctive pyroclastic flow deposit called the Povoação Ignimbrite Formation. The Povoação Ignimbrite Formation is exposed in valleys leading away from the Main caldera, within the southern coastal cliffs and extensively on the floor of the Povoação caldera, hence its name, though it was erupted from Furnas volcano. The presence of two or more densely welded ignimbritic horizons is a distinctive feature of the Povoação Ignimbrite Formation (Duncan *et al.* 1999). Guest *et al.* (1999) argue that the Povoação Ignimbrite Formation, which is dated at around 30,000 years, was probably the largest eruption of Furnas and associated with the formation of the Main caldera.

Middle Furnas Group

The Middle Furnas Group forms the fill of the Main caldera. As well as being found within the caldera there are good exposures in the cliffs along the south coast between Ponta Garça and Ribeira Quente and also within the Povoação caldera. Despite this spread of exposures it is difficult to correlate deposits beyond local areas. The products

are predominantly pyroclastic: lapilli and ash beds; ignimbrites and some lavas with material reworked by debris flows. Good exposures within the Main caldera fill are provided along the cliffs formed by the Inner caldera particularly on the northwestern shore of Lagoa das Furnas at Salto da Inglesa. In addition to the sequence of ignimbrites and fall deposits typical of the Middle Furnas Group, lacustrine sediments and pillow lavas are also exposed at Salto da Inglesa.

The collapse of the Inner caldera ended the filling phase of the Main caldera. The Pico do Ferro domes sit on top of the fill and are cut by the Inner caldera. The domes have been dated at 11,230 ± 100 BP by radiocarbon date of charcoal from the thin palaeosol that lies between the domes and the underlying ignimbrite (Moore 1991b) and the formation of the Inner caldera must be around the same age. It is possible that initiation of the caldera forming event is related to the eruption of the welded ignimbrite that underlies the Pico do Ferro domes, and that there was more than one phase of collapse.

The Pico do Canario cone was one of the youngest eruptions of the Middle Furnas Group. The cone is situated at the top of the western wall of the Inner caldera. The trachytic deposits of Pico do Canario are overlain by material from Fogo A. The Fogo A horizon (dated at around 5,000 years) is taken as marking the top of the Middle Furnas Group.

Upper Furnas Group (the last 5,000 years)

Ten trachytic eruptions have occurred on Furnas volcano over the last 5,000 years, that is since the Fogo A eruption and these are shown in Figure 4. In proximal areas the deposits include coarse lapilli beds which are relatively poorly sorted, but away from the vent area deposits typically comprise alternating fine ashes and lapilli beds indicating that each eruption involved both magmatic and hydromagmatic activity. This style of volcanism and the hazards it presents are described by Cole *et al.* (1999). As discussed by Cole *et al.* (1999), it should be noted that nine of the ten eruptions over the last 5,000 years have occurred in the latter half of this period.

Two of the eruptions have occurred since S. Miguel was settled in the mid-15th century (see Gaspar *et al.* 2015*,* this volume). The first, in c. 1439-43 AD appeared to have been taking place when the first settlers arrived from the island of Santa Maria to land at the site of what is now the village of Povoação. A priest sent to investigate what was happening in the next valley climbed to a point where he could overlook Furnas and describes what Guest *et al.* (1999) infer to be the glow of the active lava of the dome reflecting on the vapour. The next eruption and most recent of Furnas occurred in 1630 AD when the caldera was now settled by friars. The eruption began on September 3 with an explosive phase that lasted 3 days. The eruption was Sub-Plinian in style and is described in detail by Cole *et al.* (1995). It is estimated that nearly 200 people were killed.

In evaluating the hazard posed by a future eruption of Furnas based on activity over the last 5,000 years Cole *et al.* (1999) used the 1630 AD eruption as an example of activity at the lower end of the range of likely events and Furnas C, as the largest eruption of this period - to exemplify the highest magnitude event likely event. The 1630 AD eruption has already been described in detail (Cole *et al.* 1995), and, therefore a detailed description of the Furnas C is included in this paper to provide fuller information on this style of activity.

Furnas C

Furnas C is dated at around 1900 years ago (Guest *et al*. 1999) and is the largest eruption of the volcano to have occurred over the last 5000 years. The eruption built a tuff cone which broadly coincides with the area of Furnas Village (Fig. 5). The limits of the cone are not well defined due to later volcanic and tectonic activity. The preserved crater rim has a maximum diameter of 1.7 km and deposits on the north side of the cone are characterised by an alternation of ashes and coarse lapilli layers with pumice blocks reaching 74 cm and lithics larger than 30 cm. There are good exposures of proximal deposits on the west side of the cone, the basal part of the deposit consists of a coarse and lithic rich pumice layer with clast supported and matrix supported zones. Towards the top, the proportion of ash increases and the typical clast size decreases, although there are some pumice blocks reaching 40 cm and lithics bigger than 60 cm, which are often associated with prominent bomb sags. The top of the deposit is characterised by typical flow structures, showing lensoid layers and cross-bedding which are indicative of a surge origin.

This deposit represents a common eruptive style on Furnas Volcano, characterised by an alternation of magmatic and hydromagmatic activity (Cole *et al.* 1995). Booth *et al*. (1978) traced the isopachs and isopleths for the total deposit and Pacheco (1995) studied its internal structure.

Away from the vent area it is possible to trace some individual layers of Furnas C material. The deposit shows large lateral facies variation, sometimes over just a few hundred metres making correlation difficult but it is possible to identify an orthogonal sequence through the thickness of the deposit that reflects the history of the eruption Two stratigraphic units with particular characteristics are defined for the Furnas C deposit and these reflect two distinct eruptive styles. The lower unit (Unit 1, U-1), is dominated by ash layers which are largely related to hydromagmatic activity, and the upper unit (Unit 2, U-2), starts with a typical magmatic lapilli layer followed by alternating layers of ash and lapilli produced by oscillations between magmatic and hydromagmatic styles of eruption (Fig. 6).

Unit 1 (U-1)

Unit 1 covers a restricted area with a strong dispersal axis oriented towards the north (Fig. 7). The deposit essentially comprises ash with some minor sparse lapilli layers, and most of it rests directly on the preceding deposit with no trace of an intervening palaeosol. Considering the interval of 400 years that separates Furnas C from the preceding eruption, Furnas B (Booth *et al*. 1978) dated at 2,300 BP (Guest *et al*. 1999), the absence of soil in this subtropical region points to the action of a strong erosive process shortly before the deposition of U1.

U-1's ashes are light grey, except in the west quadrant where the base of the unit is yellowish. Their granulometry is fine regardless of distance from the source and the median diameter is usually finer then 3.6 ϕ. In some places coarser layers occur with rounded clasts and lateral thickness variation, traceable for some hundreds of metres, producing a stratified aspect. These are interpreted as surge deposit layers. In the uppermost part of U-1 there are some scattered *lapilli* layers of angular clasts within the ash matrix. In more distal exposures U-1 is just a massive ash layer, mantling the topography, with some well preserved delicate leaf moulds (Fig. 8) and no evident flow structures. Accretionary lapilli and vesicles are widespread.

A fairly constant granulometry, regardless of distance from source, is indicative of hydrovolcanism and the role of water is supported by the widespread occurrence of accretionary lapilli and vesicles. It is proposed that this unit has a hydromagmatic origin and was deposited as fallout with several surge layers within it, together with a few matrix supported lapilli layers resulting from an alternation between hydromagmatic and magmatic events or indeed their simultaneous occurrence.

Unit 2 (U-2)

Unit 2 is a sequence of deposits which represent discrete explosions that followed the initial hydromagmatic phase. The isopachs and isopleths of U-2 show an important dispersal axis oriented towards the north and another less pronounced one to the SSE (Fig. 9).

The base of U-2 is a relatively coarse and angular-clast supported lapilli layer, produced by the first main magmatic event of Furnas C. This is the coarsest layer of the deposit. This is followed by a sequence of alternating ash and lapilli layers produced by the oscillation between hydromagmatic and magmatic activity.

Lapilli and ash layers mantle the topography suggesting a fallout origin. Lapilli layers are progressively finer towards the top of the deposit and ash is increasingly more important. Ashes are fine grained independent of distance from the source, and show accretionary lapilli and vesicles. Lapilli layers vary from clast supported to matrix supported and the transition between ash and lapilli layers varies from sharp to

diffuse boundaries. Both clast supported and matrix supported lapilli layers comprise angular pumice clasts with some lithics. Clast supported lapilli layers are generally well sorted.

This first phase of U-2 was dispersed mainly towards the north. On the south side there are also ash and lapilli layers, but the main product of the deposit is ash, pointing to the predominance of hydromagmatic activity throughout the latter stages of the eruption. At Agrião, U-2 has an exceptionally thick set of lapilli layers which exceed 4 m. To the east and west of Agrião (Fig. 5) lapilli layers decrease regularly with distance from source and are typically modest pumice layers at the base of the unit, scattered in fine ash, mantling the topography (Fig. 9).

U-2 also has a few lapilli layers with rounded clasts and showing lateral variations in thickness, as much as 5 km from the source. These are interpreted as surge deposits. The absence of more evidence of surge deposition may be a result of the deceleration and “lofting” of the surges, as described by Cole *et al*. (1995) for other deposits of Furnas volcano, in such a way that the internal structure of the deposit would be much more continuous instead of the pinch, swell and cross stratification bedforms typical of surge deposits. Also, the caldera walls certainly acted as natural obstacles to the path of surges, confining most of these deposits to the Inner caldera.

The origin of U-2 ash, may, in part, be related to the magmatic activity that produced the lapilli layers, but hydromagmatism is considered to be important, as indicated by its fine granulometry that is independent of distance from the source, and by the occurrence of abundant accretionary lapilli and vesicles which are related to the presence of water at the time of deposition.

In the lower layers, pumice clasts are highly vesiculated. Clasts from these first magmatic events have two generations of vesicles: one generation is characterised by larger, elliptical vesicles, some of them coalescent; and the other generation consists of smaller, highly stretched vesicles. The presence of two types of vesicle in pumice clasts such as this is interpreted by Heiken and Wohletz (1991) as reflecting two stages of vesiculation, the first stage taking place during shallow magma emplacement and the second during the eruption. Towards the top of the deposit pumice clasts are less vesicular

Eruption Style

Hydromagmatic activity occurs when magma makes contact with water, either a surface or groundwater water body. If the fragmentation zone is lower than the aquifer as is the case for Vesuvius or Kilauea (Decker & Christiansen 1984;

Mastrolorenzo *et al.* 1993), magmatic activity takes place when water has no access to the disruption zone or when the disruption zone is higher than the aquifer.

Furnas Volcano currently has an active hydrothermal system and the stratigraphic history of the volcano shows evidence of caldera lakes going back to 27,000 BP (Moore 1991a), thus pointing to the importance of the hydrologic system since that time. Water generating Furnas hydromagmatic eruptions may have come either from groundwater or from caldera lakes. In either case, water-magma interaction occurred throughout the eruption with repeated fluctuations being marked by distinct layering of the deposits.

The eruption started with a hydromagmatic phase that produced a massive fallout ash deposit (U-1). Although the typical pulsatory character of hydromagmatic style was in evidence (Sheridan & Wohletz 1983), it represents a sustained activity with a steady magma-water interaction.

The second phase of Furnas C (U-2) began with a magmatic sub-plinian event that produced the coarsest layer of the deposit. Water may have been prevented from interacting with magma either by a sustained increase of magma supply or by cone building around the crater.

The eruption continued with an alternation of magmatic and hydromagmatic activity. Magmatic activity was characterised by stratified lapilli layers, produced by pulsatory events and typical of Sub-Plinian eruptions (Self 1976; Bursik 1993; Scandone & Malone 1985). This pulsatory behaviour is interpreted as being the result of a difference between the magma supply rate from a shallow reservoir and the discharge rate at the vent, so producing an oscillation of the disruption zone (Bursik 1993; Scandone & Malone 1985). This oscillation may also account for the alternation of magmatic and hydromagmatic activity.

Towards the top of the sequence, deposits representing hydromagmatic activity become predominant with the size of lapilli decreasing, suggesting a reduction of the column height. This decrease in the eruption rate might lead to a withdrawal of magma from the disruption zone allowing greater efficiency in the interaction of disrupting magma and water.

Hazards

Ten explosive eruptions of Sub-Plinian magnitude have occurred during the last 5 ka, of which six have occurred in the last 2 ka. An eruption of this magnitude is the most likely future event on Furnas (Cole *et al.* 1999; Jones *et al.* 1999). This likelihood needs to inform preparation and planning by the authorities responsible for civil defence

(Gaspar *et al.* 2015, this volume). Planning also needs to recognise that eruptions from other volcanoes on S. Miguel, particularly from Fogo and the Congro Fissural Volcanic System, present a hazard to the people living on the flanks of Furnas and within its caldera.

The extensive fumarolic activity of Furnas is also a risk mainly in the vicinity of Furnas village. The health hazards, in particular discharge of CO_2, were investigated by Baxter *et al.* (1999) who provided a map of soil gas emissions in Furnas village. More recent work on health implications of CO_2 and radon emissions is included in this volume (Viveiros *et al.* 2015, Silva *et al.* 2015 – both this volume). Wallenstein *et al.* (2007) describe the risk posed by similar diffuse emissions in the village of Ribeira Seca on the lower flanks of Fogo.

The part of the island which is dominated by Furnas volcano, experiences both tectonic and volcano-tectonic earthquakes. The seismic swarm in 2005 between Furnas and Fogo generated earthquakes which were felt in Furnas. These earthquakes caused many landslides particularly to the west of Furnas. Seismic hazard and vulnerability in S. Miguel is considered in more detail by Gaspar *et al.* and Wallenstein *et al*. (2015, both this volume).

Steep caldera walls and the sea cliffs present unstable landforms that are prone to collapse during periods of heavy rainfall and/or seismic activity. The landslides generated during intense rainfall in 1997 that inundated part of the village of Ribeira Quente demonstrated, not only the lethal impact, but also a wider disruption to communications and transport that hindered rescue. A detailed account of the hazards posed by landslides on S Miguel is provided by Marques *et al.* (2015, this volume)

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FIGURE CAPTIONS

Fig 1 View from the rim of the Inner Caldera looking south across Furnas lake. The walls on the Inner and Outer Calderas are labelled together with the vents of the two historic eruptions: (i) Gaspar, the dome of the circa 1439-43AD eruption (Furnas I) surrounded by its tuff cone and (ii) 1630 eruption dome. For an annotated sketch of the calderas from this view point see Figure 3a in Guest *et al.* (1999).

Fig 2 Map showing principal volcanological features of Furnas volcano. Adapted from Guest *et al.* (1999) with information from Carmo (2014) and Carmo *et al.* (2014*)*. (1) Salto da Inglesa, (2) Pico do Ferro, (3) 1630 AD dome, (4) Gaspar 1439-44 AD, (5) Pico Marconas, (6) Pico das Caldeiras, (7) Pico do Canario.

Fig 3 Digital Elevation Model of Furnas, Povoção and Nordeste Volcanic Systems, showing geomorphological relationships. The volcanic limits (thick black lines) represent the boundaries of the geomorphological expression of the volcanic constructs of Furnas, Povoação and Nordeste Volcanic Systems. The volcanic limits do not represent geological boundaries as such, for example products from Furnas Volcanic System drape over the adjacent Povoação caldera rim. (Figure from Duncan *et al*)

Fig 4 Schematic section showing activity of Furnas over last 5 ka (adapted from Guest *et al*. 1999)

Fig 5 Location of eruption vent of Furnas C.

Fig 6 Furnas C Lower (U-1) and Upper (U-2) units.

Fig 7 Furnas C: isopach map for Lower (U-1) unit.

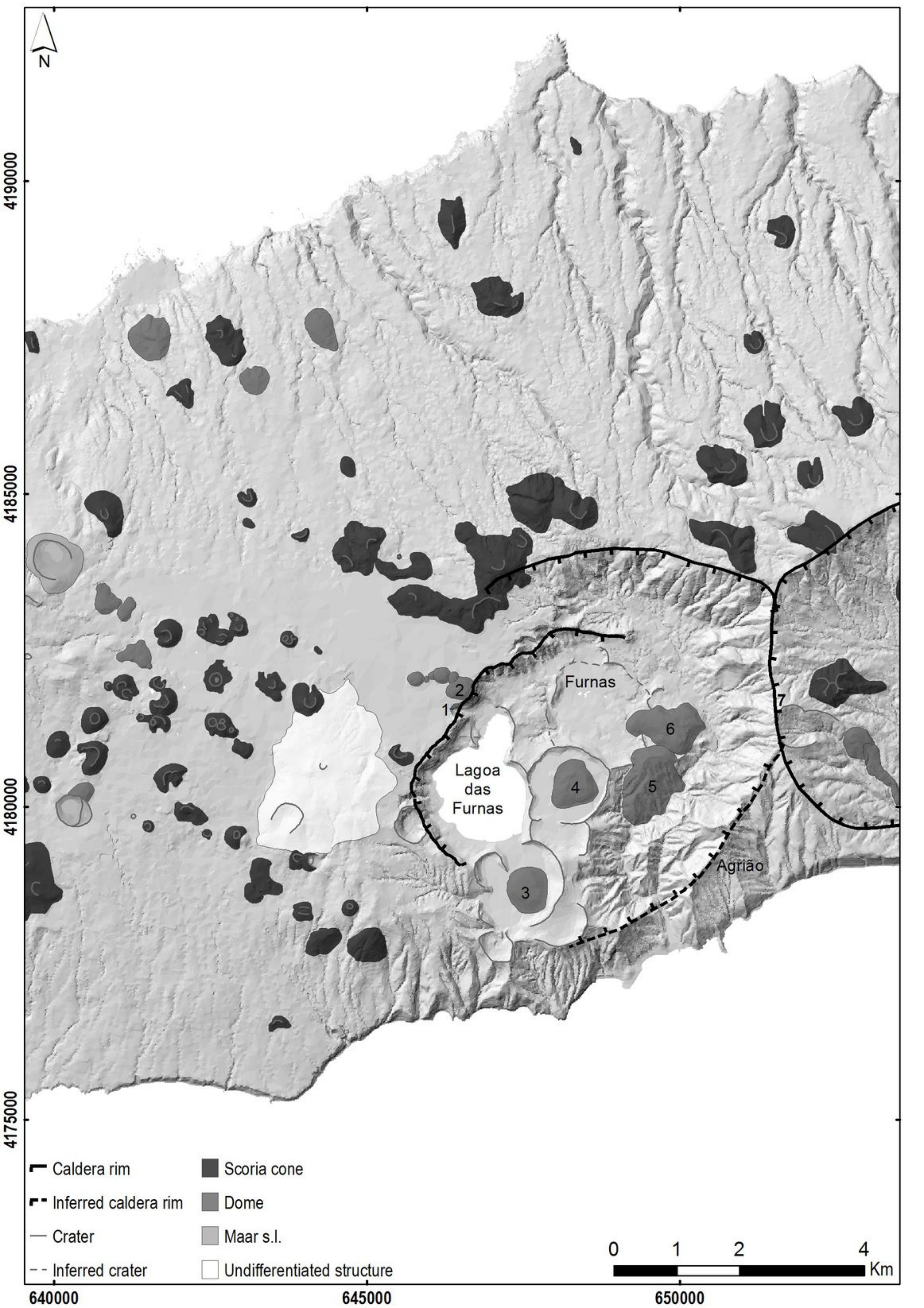
Fig 8 Leaf mould in fine ash layer from Furnas C Lower (U-1) unit.

Fig 9 Furnas C: Upper (U-2) unit (a) isopach map, (b) isopleth map for pumice and (c) isopleth map for lithics

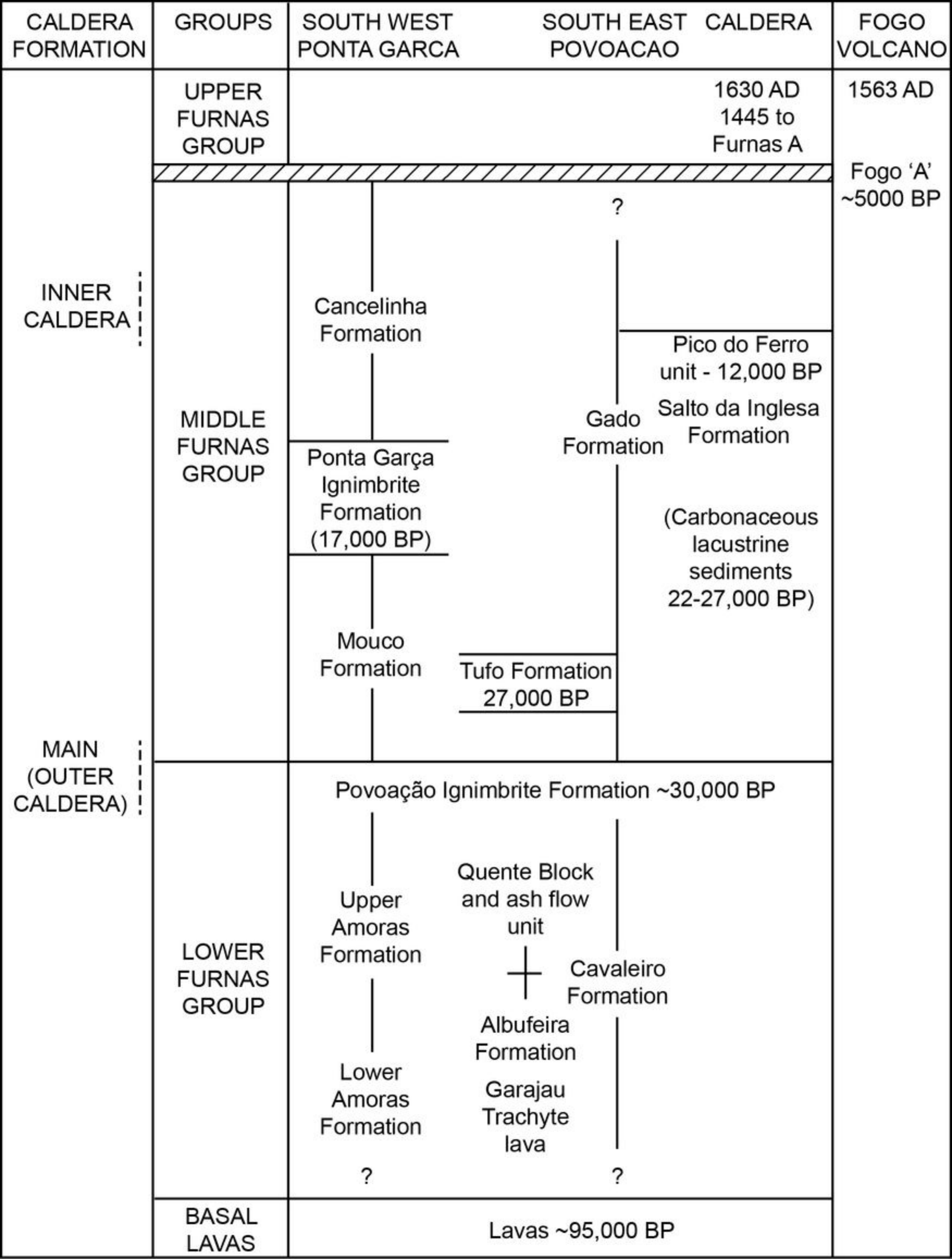
TABLE CAPTION

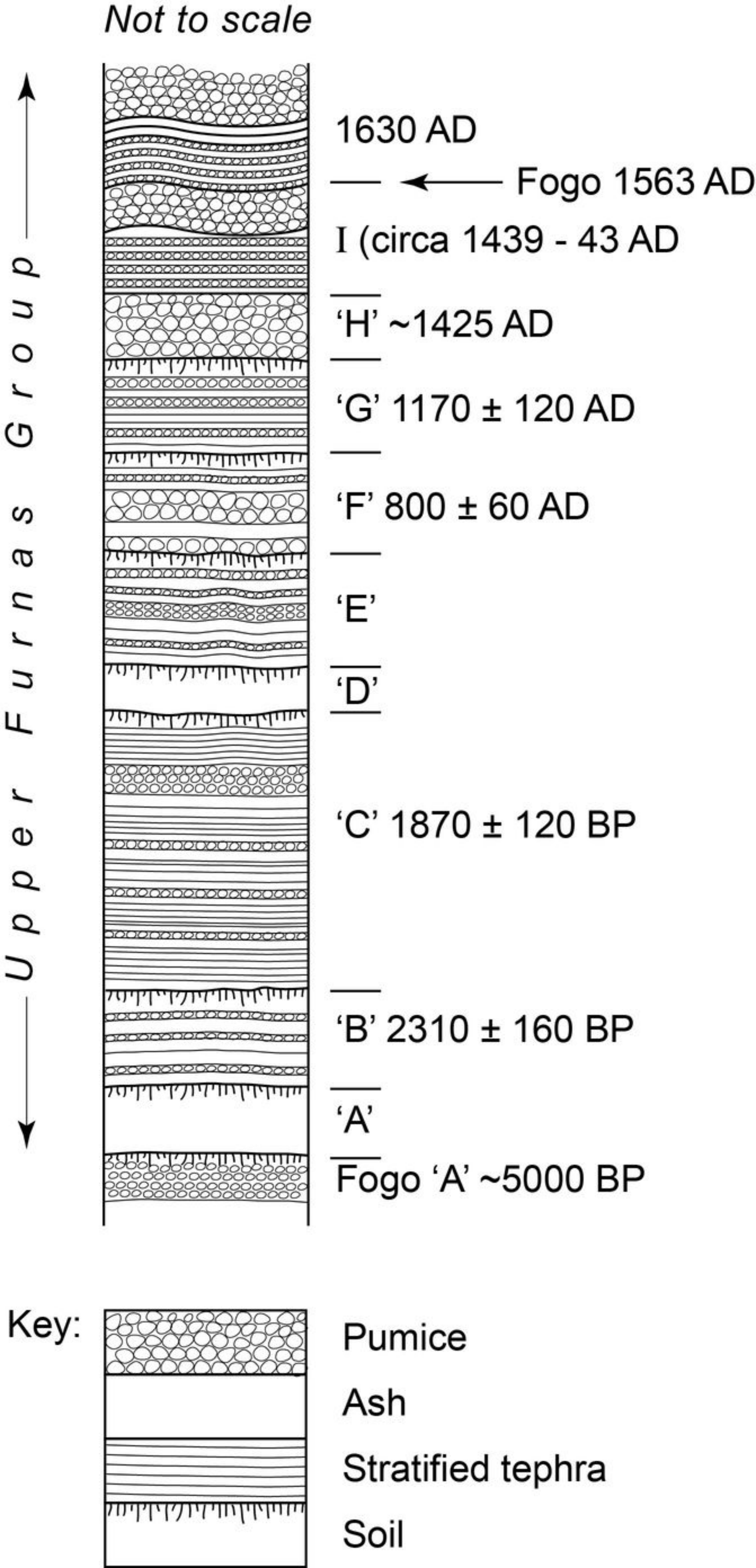
Table 1 Summary of the stratigraphy of Furnas volcano (updated from Guest *et al.* 1999)

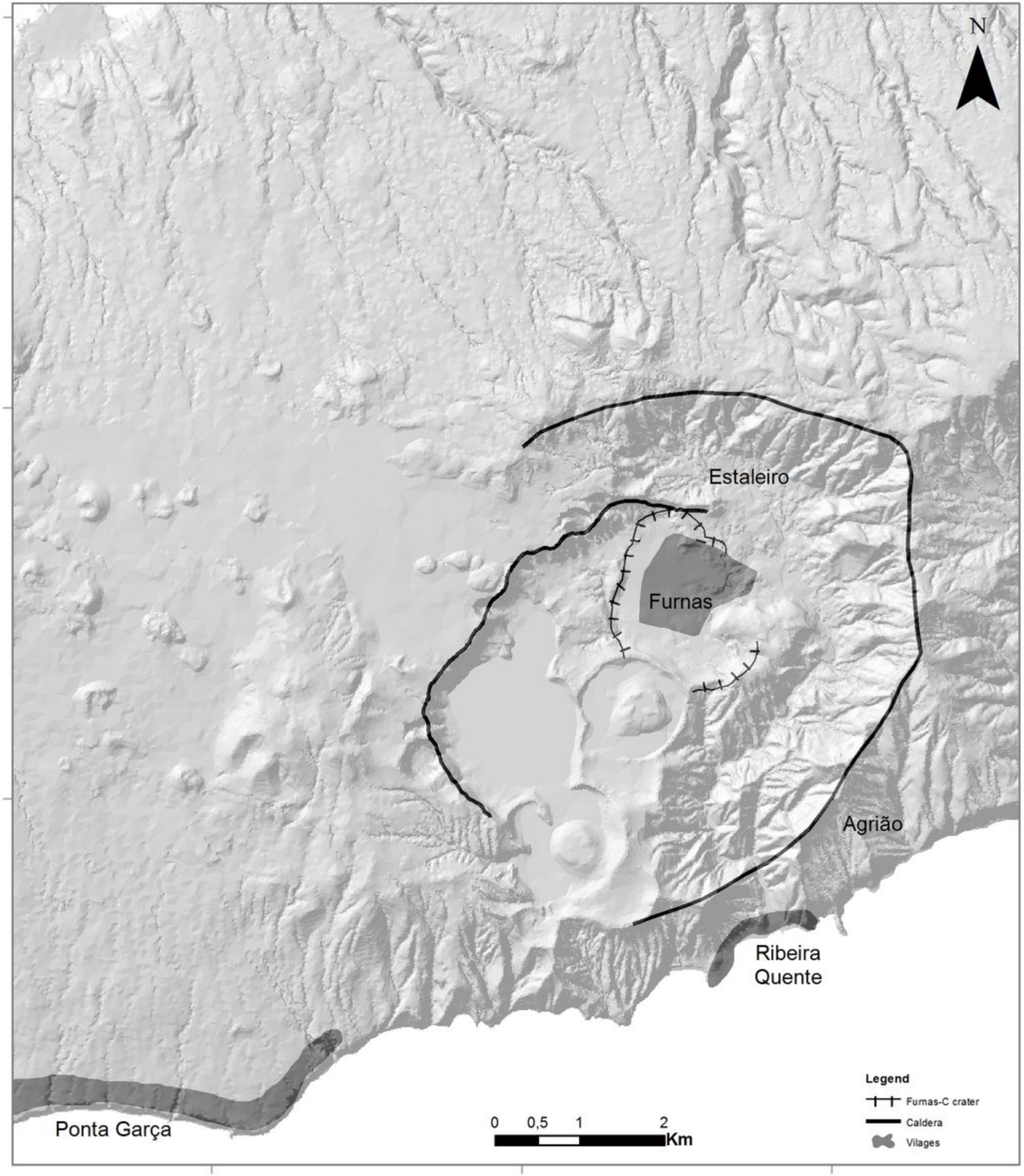

OUTER CALDERA WALL
FURNAS VILLAGE
INNER CALDERA WALL
GASPAR
1630


N
4190000
4185000
4180000
4175000
640000
645000
650000
Furnas
Lagoa
das
Furnas
Agrião
1
2
3
4
5
6
7
Caldera rim
Inferred caldera rim
Crater
Inferred crater
Scoria cone
Dome
Maar s.l.
Undifferentiated structure
0
1
2
4
Km

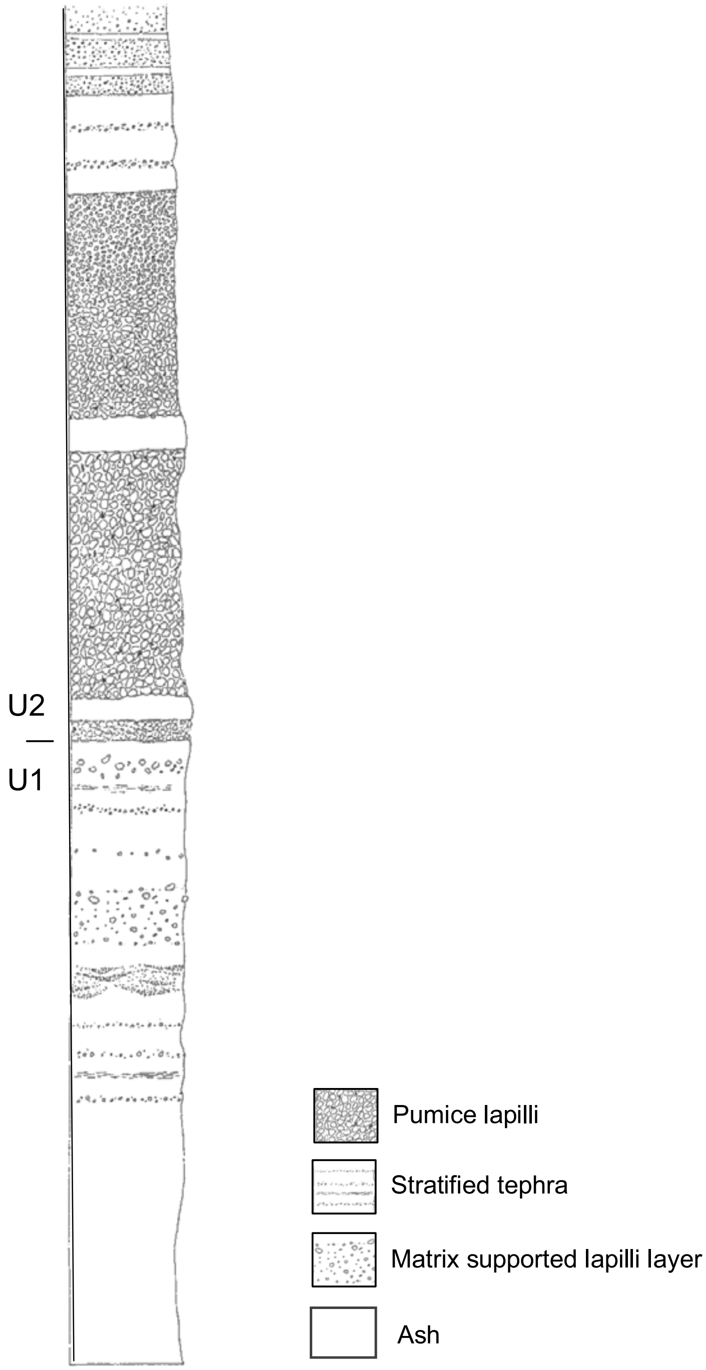
Nordeste
Povoação
Furnas
Tr
4190000
4185000
4180000
640000
645000
650000
655000
660000
665000
Caldera rim
Inferred caldera rim
Volcano limit
Inferred volcano limit
Fault
Inferred fault
Margin marine terrace

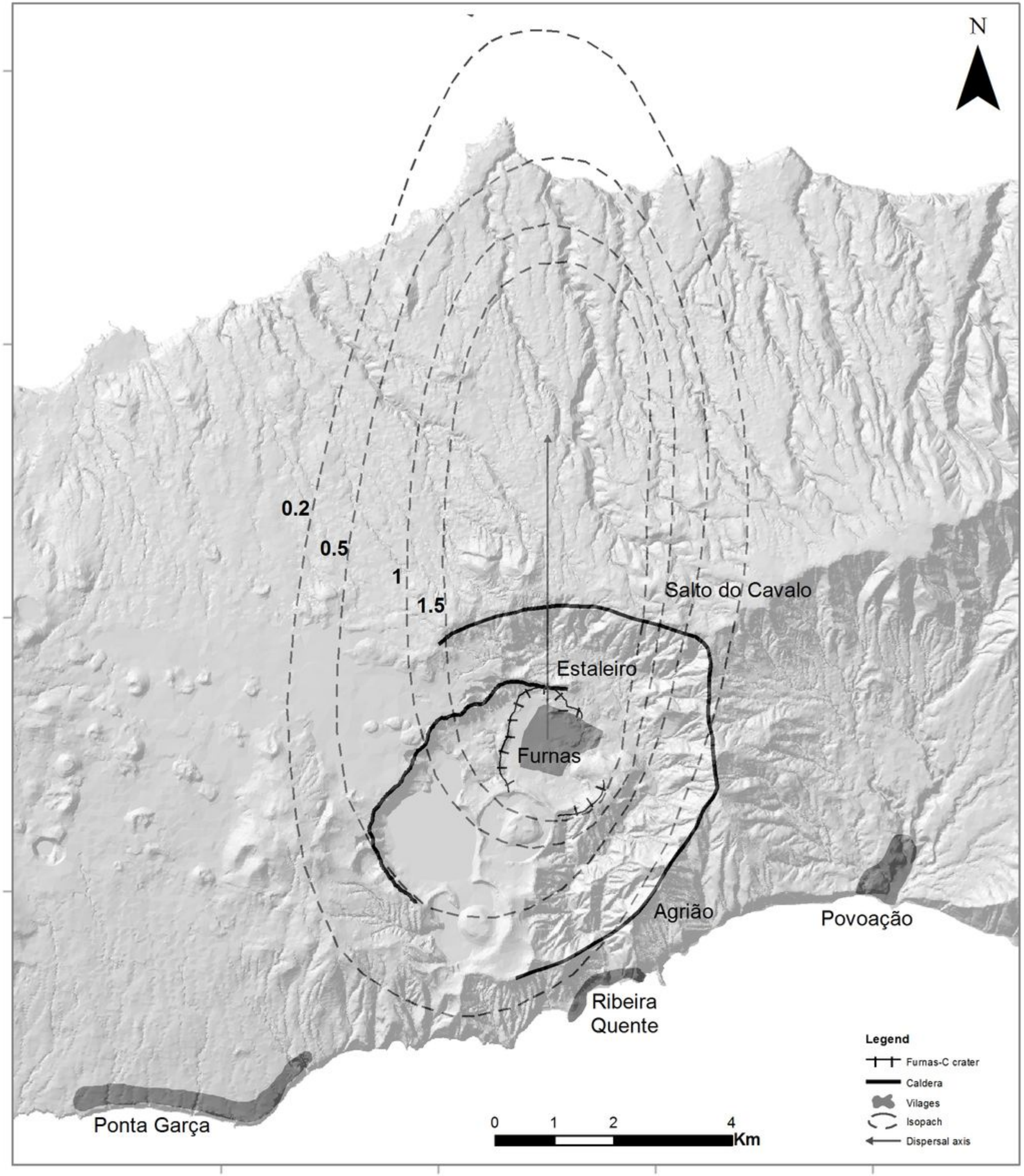

CALDERA FORMATION
GROUPS
SOUTH WEST PONTA GARCA
SOUTH EAST POVOACAO
CALDERA
FOGO VOLCANO
UPPER FURNAS GROUP
1630 AD
1445 to
Furnas A
1563 AD
Fogo 'A'
~5000 BP
?
INNER CALDERA
Cancelinha Formation
Pico do Ferro unit - 12,000 BP
MIDDLE FURNAS GROUP
Gado Formation
Salto da Inglesa Formation
Ponta Garça Ignimbrite Formation (17,000 BP)
(Carbonaceous lacustrine sediments 22-27,000 BP)
Mouco Formation
Tufo Formation 27,000 BP
MAIN (OUTER CALDERA)
Povoação Ignimbrite Formation ~30,000 BP
Quente Block and ash flow unit
Upper Amoras Formation
LOWER FURNAS GROUP
Cavaleiro Formation
Albufeira Formation
Lower Amoras Formation
Garajau Trachyte lava
?
?
BASAL LAVAS
Lavas ~95,000 BP


Not to scale
Upper Furnas Group
1630 AD
Fogo 1563 AD
I (circa 1439 - 43 AD
'H' ~1425 AD
'G' 1170 ± 120 AD
'F' 800 ± 60 AD
'E'
'D'
'C' 1870 ± 120 BP
'B' 2310 ± 160 BP
'A'
Fogo 'A' ~5000 BP
Key:
Pumice
Ash
Stratified tephra
Soil

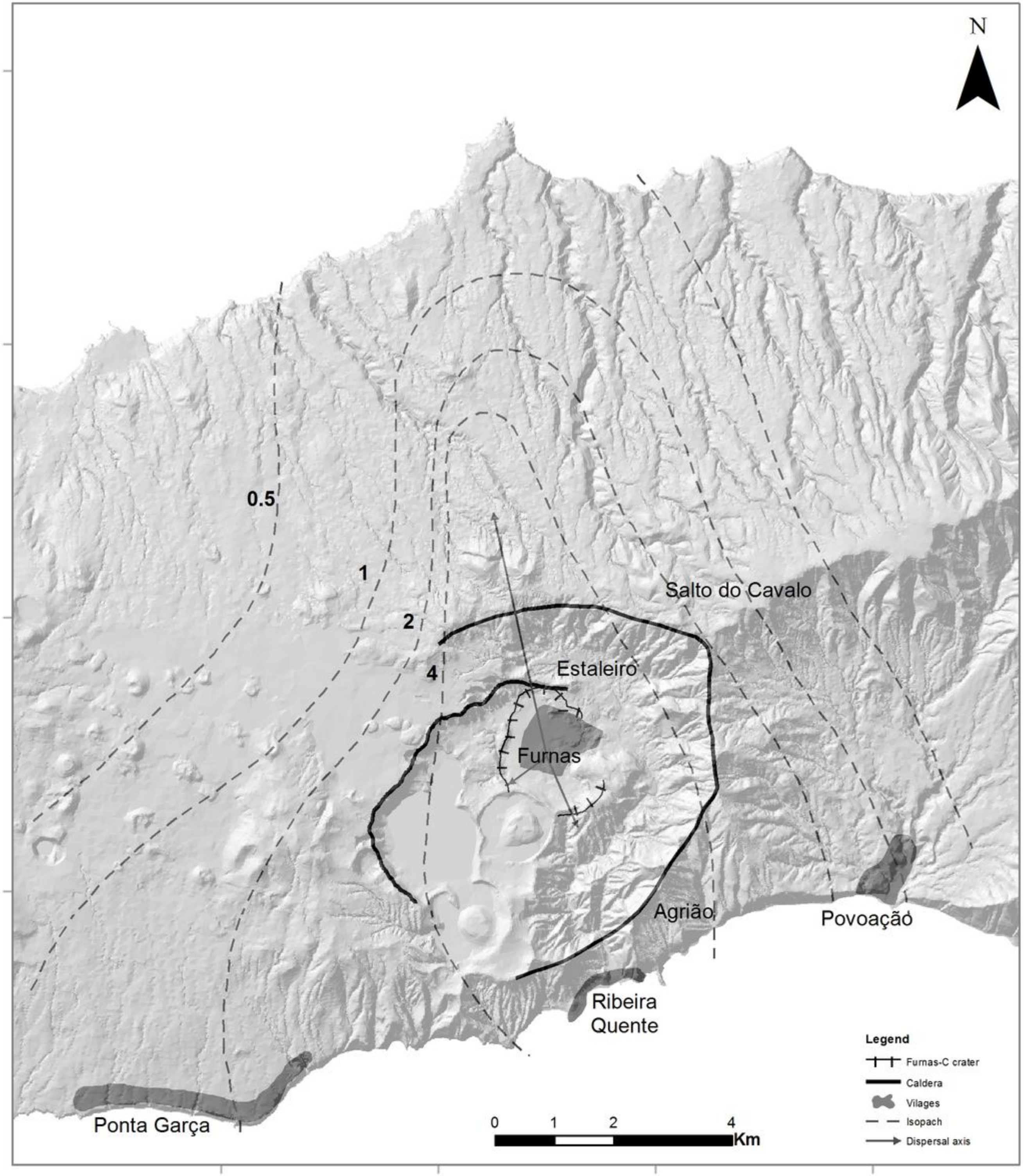


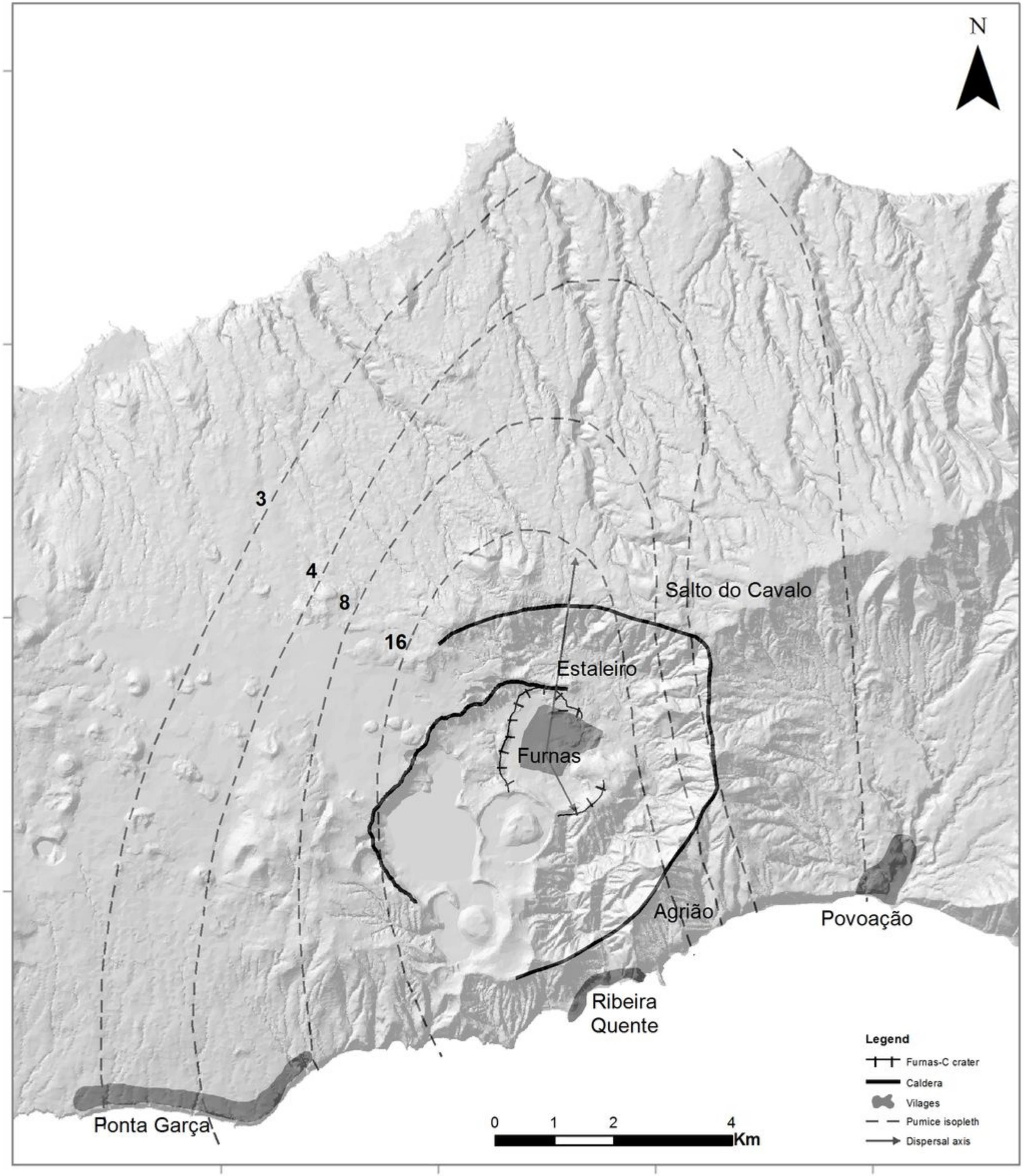
N
Estaleiro
Furnas
Agrião
Ribeira
Quente
Ponta Garça
0 0,5 1 2
Km
Legend
Furnas-C crater
Caldera
Vilages

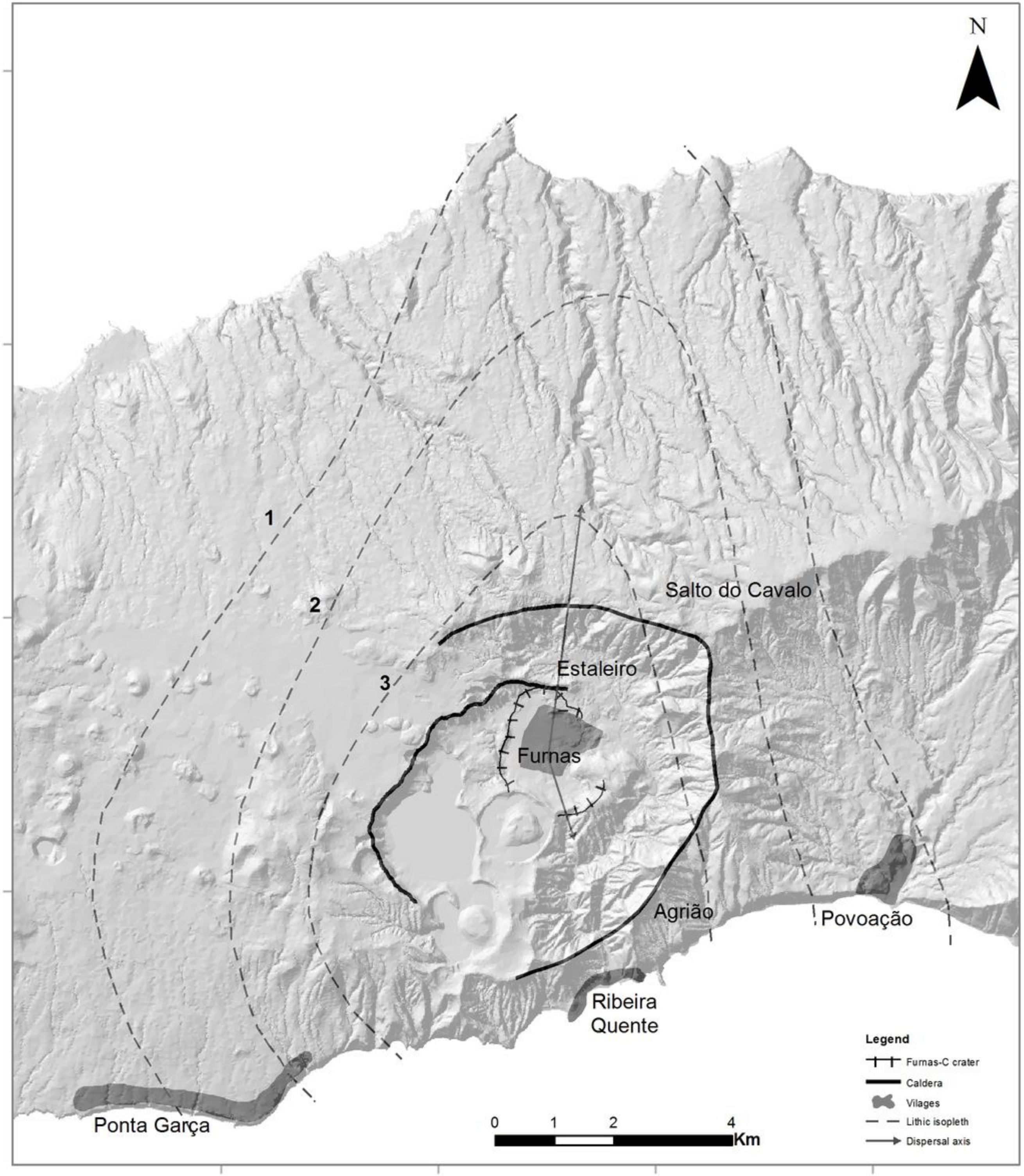

U2
U1
Pumice lapilli
Stratified tephra
Matrix supported lapilli layer
Ash


N
0.2
0.5
1
1.5
Salto do Cavalo
Estaleiro
Furnas
Agrião
Povoação
Ribeira Quente
Ponta Garça
0 1 2 4 Km
Legend
Furnas-C crater
Caldera
Vilages
Isopach
Dispersal axis

1 2 3 4 5 6 7 8 9


N
0.5
1
2
4
Salto do Cavalo
Estaleiro
Furnas
Agrião
Povoação
Ribeira
Quente
Ponta Garça
0 1 2 4
Km
Legend
Furnas-C crater
Caldera
Vilages
Isopach
Dispersal axis


N
3
4
8
16
Salto do Cavalo
Estaleiro
Furnas
Agrião
Povoação
Ribeira
Quente
Ponta Garça
0
1
2
4
Km
Legend
Furnas-C crater
Caldera
Vilages
Pumice isopleth
Dispersal axis


N
1
2
3
Salto do Cavalo
Estaleiro
Furnas
Agrião
Povoação
Ribeira
Quente
Ponta Garça
0
1
2
4
Km
Legend
Furnas-C crater
Caldera
Vilages
Lithic isopleth
Dispersal axis